Observation of the Doubly Cabibbo-Suppressed Decay $D_s^+ \to K^+K^+\pi^-$

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We report the first observation of the doubly Cabibbo-suppressed decay $D_s^+ \to K^+K^+\pi^-$ using 605 fb^{-1} of data collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. The branching ratio with respect to its Cabibbo-favored counterpart $\mathcal{B}(D_s^+ \to K^+K^+\pi^-)/\mathcal{B}(D_s^+ \to K^+K^-\pi^+)$ is $(0.229\pm0.028\pm0.012)\%$, where the first uncertainty is statistical and the second is systematic. We also report a significantly improved measurement of the doubly Cabibbo-suppressed decay $D^+ \to K^+\pi^+\pi^-$, with a branching ratio $\mathcal{B}(D^+ \to K^+\pi^+\pi^-)/\mathcal{B}(D^+ \to K^-\pi^+\pi^+)=(0.569\pm0.018\pm0.014)\%$.

Cabibbo-suppressed (CS) and doubly Cabibbo-suppressed (DCS) decays play an important role in studies of charmed hadron dynamics. CS decays of nearly all the charmed hadrons have been observed, while DCS decays have been observed for only the D^+ and D^0 mesons. The naïve expectation for the DCS decay rate is of the order of $\tan^4\theta_C$, where θ_C is the Cabibbo mixing angle [1], or about 0.29% [2] relative to its Cabibbo-favored (CF) counterpart. Current measurements [3] roughly support this expectation. It is natural to extend the searches for DCS decays to other charmed hadrons in order to further understand the decay dynamics of charmed hadrons and complete the picture.

Furthermore, one expects that the branching ratio of $D^+ \to K^+\pi^+\pi^-$ [4] is about $2\tan^4\theta_C$ relative to its CF counterpart since the phase space for $D^+ \to K^-\pi^+\pi^+$ is suppressed due to the two identical pions in the final state. This expectation is consistent with current experimental results [3]. Therefore, we also expect the branching ratio of $D_s^+ \to K^+K^+\pi^-$ is about $1/2\tan^4\theta_C$ relative to its CF counterpart. Lipkin [5] argues that SU(3) flavor symmetry [6] implies

$$\frac{\mathcal{B}(D_s^+ \to K^+K^+\pi^-)}{\mathcal{B}(D_s^+ \to K^+K^-\pi^+)} \times \frac{\mathcal{B}(D^+ \to K^+\pi^+\pi^-)}{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)} = \tan^8\theta_C, \tag{1}$$

where differences in the phase space for CF and DCS decay modes cancel in the ratios. The above relation does not take into account possible SU(3) breaking effects that could arise due to resonant intermediate states in the three-body final states considered here [5].

In this Letter, we report the first observation of the DCS decay $D_s^+ \to K^+K^+\pi^-$ and its inclusive branching ratio relative to its CF counterpart, $D_s^+ \to K^+K^-\pi^+$. We also report a new measurement of the inclusive decay rate $D^+ \to K^+\pi^+\pi^-$ relative to its CF counterpart, $D^+ \to K^-\pi^+\pi^+$. The current upper limit on $\mathcal{B}(D_s^+ \to K^+K^+\pi^-)/\mathcal{B}(D_s^+ \to K^+K^-\pi^+)$ is 0.78% at the 90% confidence level (C.L.) [7] and the world-average of the $D^+ \to K^+\pi^+\pi^-$ branching ratio is $\mathcal{B}(D^+ \to K^+\pi^+\pi^-)/\mathcal{B}(D^+ \to K^-\pi^+\pi^+)=(0.68\pm0.08)\%$ [3]. We also test the validity of prediction (1).

The data used in the analysis were recorded at the $\Upsilon(4S)$ resonance with the Belle detector [8] at the e^+e^- asymmetric-energy collider KEKB [9]. It corresponds to an integrated luminosity of 605 fb^{-1}.

D^+ and D_s^+ candidates are reconstructed using three charged tracks in the event. The initial event selection is similar to that in other Belle measurements. We require that the charged tracks originate from the vicinity of the interaction point with impact parameters in the beam direction (z-axis) and perpendicular to it of less than 4 cm and 2 cm, respectively. All charged tracks are required to have at least two associated hits in the silicon vertex detector [10], both in the z and radial directions, to assure good spatial resolution on the D mesons' decay vertices. The decay vertex is formed by fitting the three charged tracks to a common vertex and requiring a C.L. greater than 0.1%. Charged kaons and pions are identified requiring the ratio of particle identification likelihoods, $\mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_\pi)$, constructed using information from the central drift chamber, time-of-flight counters, and aerogel Cherenkov counters [11], to be larger or smaller than 0.6, respectively. In addition, we require that the scaled momentum of the charmed meson candidate $x_p = p^*/\sqrt{0.25 \cdot E_{\mathrm{CM}}^2 - M^2}$ be greater than 0.5 to suppress combinatorial background as well as D mesons produced in B meson decays. Here p^* and E_{CM} are the charmed meson momentum and the total e^+e^- collision energy, calculated in the center-of-mass frame, and M is the reconstructed invariant mass of the candidate. Figure 1 shows the $K\pi\pi$ and $KK\pi$ [12] invariant mass distributions after the initial selections. The background levels are too high to observe DCS signals.

We then apply further selection criteria, which are optimized using real data samples since there are some discrepancies between the Monte Carlo (MC) simulation [13] and the data in the relevant distributions. We use 10% of the data sample for optimization and the remaining 90% for the measurement to avoid a possible bias when the same samples are used for both optimization and the measurement. Hence the final selection criteria are obtained in a blind manner. Assuming no signal in the DCS
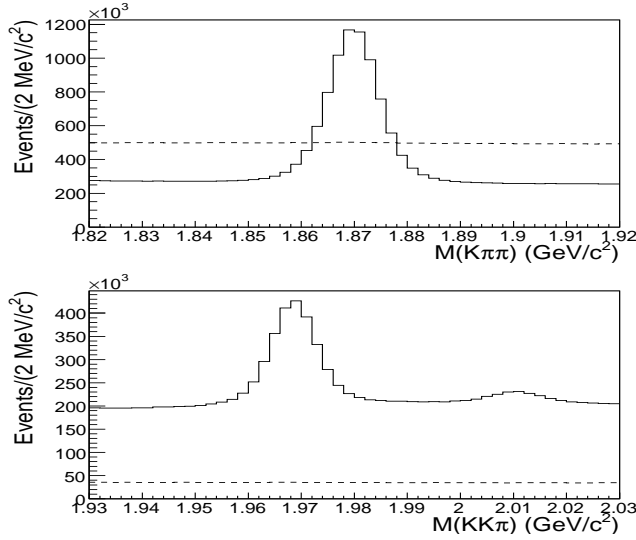
FIG. 1: $M(K\pi\pi)$ (top) and $M(KK\pi)$ (bottom) distributions after the initial selections. The solid curve shows the CF decay channel and the dashed shows the DCS decay channel in each plot.
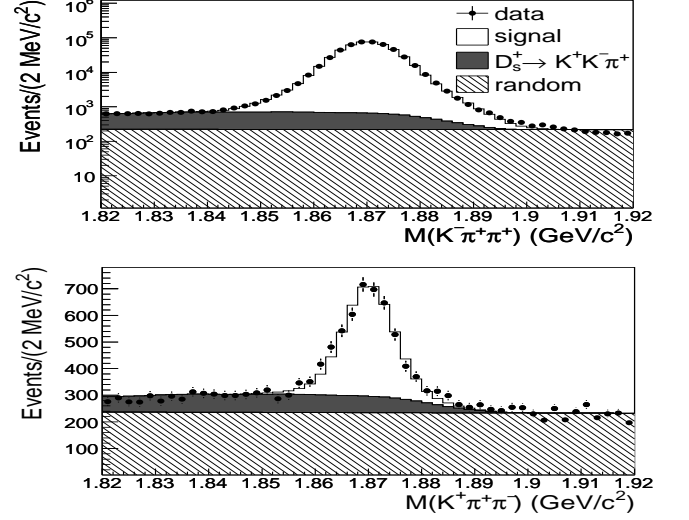
decay mass distributions.

FIG. 2: Distributions of $M(K^-\pi^+\pi^+)$ (top) and $M(K^+\pi^+\pi^-)$ (bottom). The $K^-\pi^+\pi^+$ distribution is shown on a semi-logarithmic scale to make the small background visible. Points with error bars show the data and histograms show the results of the fits described in the text. Signal, $D_s^+ \to K^+K^-\pi^+$ background, and random combinatorial background components are also shown.

decay channel, we maximize $\mathcal{N}_S/\sqrt{\mathcal{N}_B}$, where $\mathcal{N}_S$ is the CF signal yield which has similar properties to the DCS signal and $\mathcal{N}_B$ is the background yield from the sideband regions in the DCS sample.

One of the selections related to the finite lifetime of charmed hadrons is the reduced χ^2 (χ^2/d.o.f) for the hypothesis that the candidate tracks for the charmed meson decay products arise from the primary vertex. The primary vertex is obtained as the most probable point of intersection of the meson's momentum vector and the e^+e^- interaction region. Due to the finite lifetime of D^+ and D_s^+ mesons their daughter tracks are not likely to be compatible with the primary vertex. The second requirement uses the angle between the charmed meson momentum vector, as reconstructed from the daughter tracks, and the vector joining its production and decay vertices. In an ideal case without resolution the two vectors would be parallel for the signal. The reduced χ^2 is required to be greater than 25 for D^+ and 5 for D_s^+ candidates and the angle is required to be less than $1°$ for D^+ and $2°$ for D_s^+ candidates. Tighter requirements on charged kaon identification (>0.9) and x_p (>0.7) are also chosen for the final selection, which improves the signal sensitivity. After the additional and tighter selection requirements described above, 9.57% of D^+ and 10.71% of D_s^+ CF signal, and 0.06% of D^+ and 0.24% of D_s^+ DCS background events are retained. In order to minimize systematic effects we choose the same selection criteria for both DCS and CF decay channels. The $K\pi\pi$ and $KK\pi$ invariant mass distributions after the final selections are shown in Figs. 2 and 3 together with signal and background parameterizations. A clear signal is observed in both DCS

The $K\pi\pi$ and $KK\pi$ invariant mass distributions are fitted using the binned maximum likelihood method. In all cases the signal probability density function (PDF) is parameterized using two Gaussians with the same central value. Due to K/π misidentification the following reflection backgrounds appear in the mass distributions. In $D^+ \to K^-\pi^+\pi^+$ (CF) and $K^+\pi^+\pi^-$ (DCS) decays there is a contribution from misidentified $D_s^+ \to K^+K^-\pi^+$ decay; in $D_s^+ \to K^+K^-\pi^+$ (CF) decay there is a contribution from misidentified $D^+ \to K^-\pi^+\pi^+$; and in $D_s^+ \to K^+K^+\pi^-$ (DCS) decay there is a contribution from misidentified $D^+ \to K^+\pi^+\pi^-$ decay. The PDFs for the reflection backgrounds are determined from real data by assigning the nominal pion (kaon) mass to a kaon (pion) track. The magnitude of each of the reflection background contributions is a free parameter in the fit. For the DCS D_s^+ channel, the $D^+ \to K^+\pi^+\pi^-$ contribution is not incorporated in the fit since it is not significant, but its effect is included as a systematic uncertainty due to fitting listed in Table II. The D^{*+} contribution ($D^{*+} \to D^0\pi^+$ with $D^0 \to K^+K^-$) in the CF D_s^+ channel is also incorporated in the CF D_s^+ fit as an independent Gaussian component. A linear function is used for the random combinatorial background for all channels. All signal and background parameters for the CF channels are floated. For the DCS channels the mass, width, and ratio of the two signal Gaussians are fixed to the values obtained from the fits to distributions of CF decays. Signal and background yields are left free in the fit. From
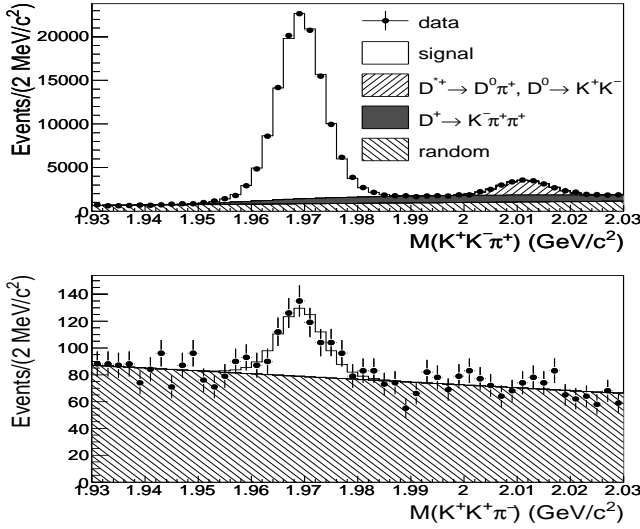
FIG. 3: Distributions of $M(K^+K^-\pi^+)$ (top) and $M(K^+K^+\pi^-)$ (bottom). Points with error bars show the data and histograms show the results of the fits described in the text. Signal, D^{*+} background ($D^{*+} \to D^0\pi^+$ where $D^0 \to K^+K^-$), $D^+ \to K^-\pi^+\pi^+$ background, and random combinatorial background components are also shown.

the results of the fits, shown in Figs. 2 and 3, we extract the signal yield for each channel, listed together with the corresponding branching ratios in Table I.

The statistical significance of the $D_s^+ \to K^+K^+\pi^-$ signal is calculated using $-2\ln(\mathcal{L}_b/\mathcal{L}_{s+b})$ where $\mathcal{L}_b$ and $\mathcal{L}_{s+b}$ are the likelihood values of the fit, without and with the signal PDF included, respectively. We find $-2\ln(\mathcal{L}_b/\mathcal{L}_{s+b})$=83.2 with one degree of freedom used to describe the DCS signal yield; we obtain a statistical significance corresponding to 9.1 standard deviations.

In addition to the backgrounds mentioned above there is also the possibility of double misidentification leading to contributions from CF events to the DCS sample. MC simulation shows that such a contribution is flat in the invariant mass distribution and is hence included in the combinatorial background description.

The final states in this study have resonant substructure that can affect the reconstruction efficiency. The resonances are relatively well known for the decay modes other than $D_s^+ \to K^+K^+\pi^-$. We used a coherent mixture of resonant contributions according to [14] to generate $D^+ \to K^-\pi^+\pi^+$ decays and calculate the reconstruction efficiency. For the $D^+ \to K^+\pi^+\pi^-$ and $D_s^+ \to K^+K^-\pi^+$ decays we used an incoherent mixture of intermediate states [3]. Subsequently we varied the contributions of individual intermediate states in a correlated manner, within the uncertainties of the measured branching fractions. The efficiency calculated from the modified MC sample differs from the original one by 1.5% and 2.0% for the $D^+ \to K^+\pi^+\pi^-$ and $D_s^+ \to K^+K^-\pi^+$ decays, respectively, and the differ-

ence was included in the systematic uncertainty of the result. $D_s^+ \to K^+K^+\pi^-$ decays were generated according to phase space. For comparison, signal events were generated assuming either $K^{*0}(892)K^+$ or $K^{*0}(1430)K^+$ intermediate states. The largest relative difference in the efficiency (2.4%) was included as a part of the systematic uncertainty. Ratios of reconstruction efficiencies for DCS and CF decays are found to be 1.042±0.008±0.016 and 0.963±0.010±0.030 for D^+ and D_s^+ decays, respectively, where the first uncertainty is due to the finite MC simulation statistics and the second is the uncertainty in the resonant structure of the final states.

With the efficiencies estimated above, we measure the inclusive branching ratios of DCS decays relative to their CF counterparts summarized in Table I. The product of the branching ratios for the two DCS decay modes is found to be $\frac{\mathcal{B}(D_s^+ \to K^+K^+\pi^-)}{\mathcal{B}(D_s^+ \to K^+K^-\pi^+)} \times \frac{\mathcal{B}(D^+ \to K^+\pi^+\pi^-)}{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)} = (1.57 \pm 0.21) \times \tan^8\theta_C$, where the error is the total uncertainty.

TABLE I: Measured branching ratios. $\mathcal{B}_{\rm rel.}$ is the branching ratio relative to $D^+ \to K^-\pi^+\pi^+$ for the D^+ modes and $D_s^+ \to K^+K^-\pi^+$ for the D_s^+ modes. The uncertainties in the branching ratios are statistical and systematic.

Decay Mode	$\mathcal{N}_{\rm signal}$	$\mathcal{B}_{\rm rel.}(\%)$
$D^+ \to K^+\pi^+\pi^-$	2637.7±84.4	0.569±0.018±0.014
$D^+ \to K^-\pi^+\pi^+$	482702±727	100
$D_s^+ \to K^+K^+\pi^-$	281.4±33.8	0.229±0.028±0.012
$D_s^+ \to K^+K^-\pi^+$	118127±452	100

Several sources of systematic uncertainty cancel in the branching ratio calculation due to the similar kinematics of CF and DCS decays (for example, uncertainties in the tracking efficiencies and particle identification, since the momenta of the final state tracks are almost identical). The stability of the branching ratios against the variation of the selection criteria was studied and we observed no changes greater than the expected statistical fluctuations. The systematic uncertainties due to the variation of the fit parameters are 1.9% for D^+ and 4.2% for D_s^+ branching ratios measurements, respectively. Table II summarizes the systematic uncertainties in the measurements of the branching ratios.

TABLE II: Relative systematic uncertainties in percent, where $\sigma_{\mathcal{B}_{\rm rel.}(D^+)}$ and $\sigma_{\mathcal{B}_{\rm rel.}(D_s^+)}$ are systematic uncertainties for the branching ratio of D^+ and D_s^+ DCS decays relative to their CF counterparts.

Source	$\sigma_{\mathcal{B}_{\rm rel.}(D^+)}$ (%)	$\sigma_{\mathcal{B}_{\rm rel.}(D_s^+)}$ (%)
Fitting	1.9	4.2
MC Statistics	0.8	1.0
Reconstruction Efficiency	1.5	3.1
Total	2.5	5.3

Using the world-average values $\mathcal{B}(D^+ \to K^-\pi^+\pi^+) = (9.22 \pm 0.21)\%$ and $\mathcal{B}(D_s^+ \to K^+K^-\pi^+) = (5.50 \pm 0.28)\%$ [3], we obtain the absolute branching fraction for each DCS decay channel. Table III shows the results and the comparison to previous results.

TABLE III: Absolute branching fraction for each decay mode and comparisons with previous measurements. The first uncertainties shown in the second column are the total uncertainties of our results and the second are the uncertainties in the average CF branching fractions used for normalization [3].

Branching Fraction	Belle	World-Average [3]
$\mathcal{B}(D^+ \to K^+\pi^+\pi^-)$	$(5.2\pm0.2\pm0.1)\times10^{-4}$	$(6.2\pm0.7)\times10^{-4}$
$\mathcal{B}(D_s^+ \to K^+K^+\pi^-)$	$(1.3\pm0.2\pm0.1)\times10^{-4}$	$(2.9\pm1.1)\times10^{-4}$

To conclude, using 605 fb^{-1} of data collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider we have observed for the first time the decay $D_s^+ \to K^+K^+\pi^-$ with a statistical significance of 9.1 standard deviations. This is the first DCS decay mode of the D_s^+ meson. The branching ratio with respect to the CF decay is $(0.229\pm0.028\pm0.012)\%$, where the first uncertainty is statistical and the second is systematic. We have also determined the D^+ DCS decay branching ratio, $\mathcal{B}(D^+ \to K^+\pi^+\pi^-)/\mathcal{B}(D^+ \to K^-\pi^+\pi^+)=(0.569\pm0.018\pm0.014)\%$, where the first uncertainty is statistical and the second is systematic, with a significantly improved precision compared to the current world-average [3]. We find the product of the two relative branching ratios, $\frac{\mathcal{B}(D_s^+\to K^+K^+\pi^-)}{\mathcal{B}(D_s^+\to K^+K^-\pi^+)} \times \frac{\mathcal{B}(D^+\to K^+\pi^+\pi^-)}{\mathcal{B}(D^+\to K^-\pi^+\pi^+)}$ to be $(1.57\pm0.21)\times \tan^8\theta_C$. This is consistent with SU(3) flavor symmetry within three standard deviations; note that the effect of (different) resonant intermediate states is not taken into account in the prediction [5]. An amplitude analysis on a larger data sample may allow a more precise test of SU(3) flavor symmetry to be performed.

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